Assessing the design of the NSW-IMOS Moored Observation Array from 2008-2013: Recommendations for the future.

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***Abstract*—An array of 8 moorings has been deployed on the continental shelf along the coast of southeastern Australia as part of the New South Wales node of Australia's Integrated Marine Observing System. The array which was first deployed in 2008, was designed to capture the key continental shelf processes associated with the flow of the East Australian Current along the narrow continental shelf off southeastern Australia.**

As with every such observing program, the initial experimental design is made using the best information available at the time of the design phase. In the case of NSW-IMOS, there were a very limited number of long term observations with which to make an informed decision. The first of the NSW-IMOS moorings was installed in mid-2008 providing more than 4 years of high resolution timeseries data. Parameters measured include current velocity and temperature, salinity, fluorescence, dissolved oxygen and turbidity.

In this paper we describe the NSW-IMOS array and its design rationale. We discuss some of the key results to date and then make an assessment of the array based on metrics such as data coverage, data quality, data coherence (vertical) and correlation (spatial) and finally data uptake. We make some informed recommendations for the short term consolidation of the array in the face of recent budget cuts. We suggest improvements to the array for such times as additional funding is forthcoming. Finally we propose ideas for the use of data assimilation modelling to provide a more comprehensive assessment of the array and its utility in diagnosing coastal circulation in the EAC.

I. Introduction

With the development of the NSW node of Australia's Integrated Marine Observing System (NSW-IMOS, (www.imos.org.au, [1], [2]), an array of 8 moorings has been deployed on the continental shelf along the coast of southeastern Australia. The array was designed to capture the key continental shelf processes along the narrow continental shelf of southeastern Australia. The East Australian Current (EAC) flows southward along the east coast of New South Wales, transporting heat poleward. It drives upwelling in coastal waters [3]–[5] and enhances productivity e.g. [6], [7] and biological connectivity [8], [9]. Processes of interest include both wind and current driven upwelling, internal waves, and cross-shelf processes associated with the encroachment or separation of the EAC and its eddy field.

A. Science Objectives

The NSW-IMOS node science and implementation plan (http://imos.org.au/plans.html) outlines an ambitious set of objectives spanning multiple disciplines, (from physics to fish) and multiple scales (both space and time). Questions range from addressing fundamental climate change questions to understanding the movement of tagged fish and the relationship to their physical environment. Of direct relevance here however are questions pertaining to the continental shelf processes on the inshore edge of the east Australian current. Specifically, core goals 3 and 4 of the node science and implementation plan (Sept 2010) are:

1) To investigate the EAC, its separation from the coast, and the resultant eddy field along the coast of SE Australia.
    a) To determine the frequency, form and function (horizontal and vertical) of EAC eddies;
    b) To understand air sea interactions, particularly to determine the development of East Coast Lows and severe winter storms in relation to warm core eddies;
    c) Quantify the impact of key physical processes such as onshore encroachment of the EAC, slope water intrusions, upwelling, downwelling and internal waves.
2) To quantify oceanographic processes on the continental shelf and slope of SE Australia:
    a) Examine the coastal wind and wave climate in driving nearshore currents and the northward sediment transport;
    b) Quantify the biogeochemical cycling of carbon (nutrients and phytoplankton composition);
    c) Determine the transport and dispersal of passive particles (e.g. larvae, eggs, spores) and the degree of along coast connectivity and trophic linkages.

In the light of these science objectives, three focal sites were chosen for oceanographic mooring arrays: Coffs Harbour, Sydney and Narooma. Coffs Harbour lies approximately 550 km to the north of Sydney while Narooma (BMP pair) lies approximately 350 km to the south. These are the only permanent moorings along an approximately 2000 km stretch of coastline and their location is intended to represent the dynamics upstream of the EAC separation point (CH) and downstream (SYD) as well as the EAC extension (BMP).

II. Methods

A. Designing The Observing System

During the design phase of IMOS (2006-2008) there were a very limited number of long term observations with which to make informed decisions. Apart from the single mooring at the Ocean Reference Station (ORS065, Figure 1) and the long term hydrographic sampling sites at Port Hacking (e.g PH100, Figure 1, since the 1940s) the only other moored observations came from short term process studies which were typically limited in spatial and temporal coverage (e.g [10], in southern NSW, [11], off Sydney, [4], straddling the EAC separation point and [12] off northern NSW where the EAC is typically most coherent). We chose to design a mooring array to provide high vertical and temporal resolution of key parameters. The mooring array is complemented by other components of the observing system, including HF Radar and repeat glider deployments as shown in Figure 1.

B. The Design of the NSW-IMOS Mooring Array

Deploying moorings is always a difficult trade off between science objectives, security, practicality, and cost. Unfortunately science objectives tend to get compromised in the face of the other competing demands. For example, in the case of security off the coast of southeastern Australia there is an active bottom trawl fishery which poses a threat to any bottom mounted mooring, and very busy surface shipping lanes accessing some of Australia's largest ports. Any surface float is a magnet for recreational fishers who tie up to the mooring line and cause unintentional damage, or possibly even vandalism. Finally, in this region the surface current can reach greater than 4 knots [5], [13], so any surface float needs to be of significant size (with a suitably large bottom weight, and hence deployment vessel) which increases the budget significantly. Moving moorings further offshore to the shelf break is always desirable, however the distance from the coast then precludes a day trip (practicality, cost), and increases the load on the mooring due to the increase in current strength (cost).

Presently the PH100, SYD100, SYD140, CH070 and CH100 moorings (Table I) consist of a bottom mounted TRDI 300 kHz ADCP and a string of Aquatech 520 temperature and temperature/pressure loggers at 8 m intervals through the water column. The line of thermistors is supported by a float, approximately 20 m below the surface. Below the sub-surface float at SYD100 (and intermittently at PH100) is a Wetlabs water quality meter (WQM) that consists of a SeaBird CTD, as well as measurements of fluorescence, and turbidity (Wetlabs FLNTU) and dissolved oxygen. The BMP moorings (BMP090 and BMP120) consist of thermistor / pressure string only. Temperature and velocity data are recorded at 5 min intervals while the WQM records 60 burst samples at a rate of 1 Hz, every 15 mins.

The ORS065 mooring has been maintained by Sydney Water since 1989 and the data is provided freely as an in kind contribution to IMOS. The first of the IMOS moorings (SYD100 and SYD140) were deployed in June 2008 (Table I). The CH pair (CH070 and CH100) were deployed late 2009 with some initial teething problems resulting in the good data from 2010 onwards.

In November 2009 an additional mooring was deployed at PH100, while the final mooring pair was deployed off Narooma (BMP090 and BMP120) in March 2011. Instrumentation was added to the PH100 mooring in stages as the security of the site became trusted. Initially a t-string was deployed. A WQM was added in May 2010 at approximately 20 m below the surface, and a bottom mounted ADCP was added when additional funding was acquired in April 2011. This mooring was also augmented with a stand alone surface float (for added security), which allowed for the measurement of temperature immediately below the surface. Other than this the configuration was identical to that of the SYD100 mooring. Unfortunately the entire mooring was lost in May 2012 due to a suspected trawler strike. The Port Hacking site is one of a series of nine national reference stations located around Australia [14].

The data coverage to date is shown in Figure 2. While there have been a number of data losses due to instrument failure or other (as above) the data return has been in the order of $75-99\%$ successful.

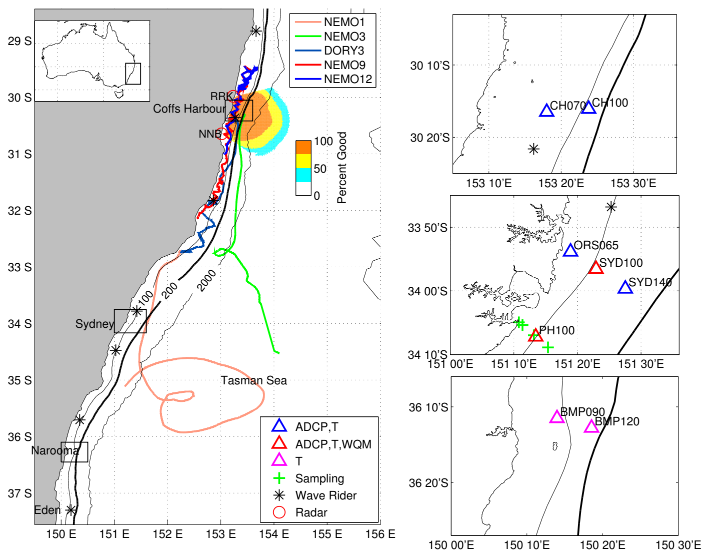

Fig. 1: Map of NSW-IMOS region showing locations of the moorings and their sensors, the coverage of the HF radar system (as a percentage of good data), and the track from a number of the slocum (Nemo) and seaglider (Dory) missions along the continental shelf edge and into EAC eddies.

Platform Code	Latitude S	Longitude E	Depth (m)	Dist (km)	Date Deployed	Length Days	Approx % Coverage
CH070	30°17.00′	153°17.91′	70	15	15 Aug 2009	1352	85
CH100	30°16.07′	153°23.80′	100	22.2	15 Aug 2009	1265	79
ORS065*	33°53.88′	151°18.9′	65	2.1	29 May 2008	1758	99
SYD100	33°56.63′	151°23.03′	100	9.9	25 Jun 2008	1654	91
SYD140	34°00.08′	151°27.92′	140	19	25 Jun 2008	1652	88
PH100	34°06.98′	151°13.14′	100	6.1	29 Oct 2009	1045	77
BMP090	36°11.5′	150°14.0′	90	8.9	30 Mar 2011	595	90
BMP120	36°12.9′	150°18.50′	120	16.1	30 Mar 2011	657	99

TABLE I: Details of NSW-IMOS mooring sites, position, depth, distance from the shore and deployment date. $\star$ - ORS065 is maintained under contract for Sydney Water Corp. since 1989, and has been included as an in-kind contribution to IMOS since 29 May 2008. Percent coverage is calculated based on the temperature records and considers the number of thermistors in the vertical and the temporal sampling interval.

III. Assessing the Design of the Array

A number of metrics are used to assess the design of the moored instrument array and its utility in helping to address the fundamental science questions in the NSW-IMOS node science and implementation plan. We use metrics such as Data coverage, the length of the timeseries and the quality of the data, versus the expected number of data points. We investigate the vertical correlation between sensor records through the water column, the autocorrelation in time, and the horizontal correlation in space. In the face of budget cuts, cost savings measures are suggested and addressed, including: decreasing the vertical instrument density in the array (saving instruments that can't be replaced), decreasing the sampling interval (increasing battery and memory life, thus potentially reducing servicing interval), and potentially removing entire moorings, if the data are found to be well correlated with adjacent data streams.

A. Data Coverage

In the context of sustained observing, minimising data gaps is critical. Data gaps can occur from any combination of multiple scenarios such as, instrument failure, (e.g. from failure of lithium battery cells, external power connectors, housing leaking), bio-fouling (e.g degrading sensors or sealing release units shut), operator error (e.g incorrect instrument settings, poor instrument preparation: o-rings, seals, batteries etc) and total mooring loss (e.g bottom-trawler strike, surface boat strike, failed releases, vandalism, complicated deployment scenarios etc). Some of these failures are preventable and the goal is to minimise all of the risks as best as possible. In order to assess the quality of the data stream in the context of sustained observing, calculating the data coverage readily highlights data gaps. While this metric cannot be used without qualification, it certainly identifies regions or platforms that perform better (or worse) than others.

Data coverage for the NSW-IMOS array is shown in Figure 2. Where gaps at the end of the records indicate moorings either still in the water, or data not QC'd at time of writing. Data coverage has been calculated based on the number of sensors (records) in the vertical as well as the temporal sampling interval. The longest records (more than 1650) are along the SYD transect, first deployed mid 2008 (Table I). Percent good data based on the temperature records ranges $77-99\%$, with velocity records suffering more from instrument failure ($68-97\%$, Figure 2). Large gaps exist in the BGC records due to the failure of the instruments used (Wetlabs WQM). These instruments will be phased out.

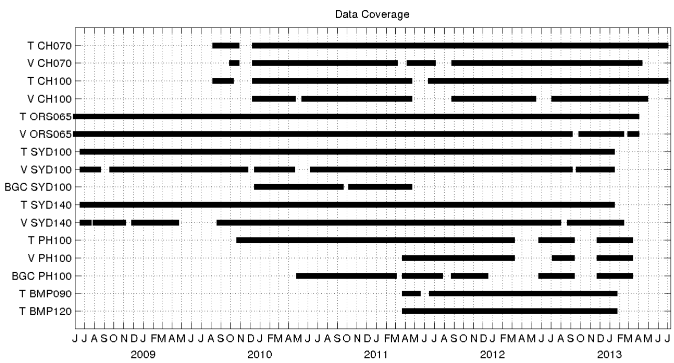

Fig. 2: Data return from the NSW-IMOS mooring array from each of the moorings as identified in Table I and Figure 1. Temperature, velocity and Biogeochemistry sensors are indicated by T, V and BGC respectively.

B. Spatial Correlation

Spatial correlations were calculated between the along (black) and across-shelf (grey) components of the sub-inertial depth-integrated velocities as well as the lags, between each mooring pair (Table II). We used the maximum concomitant time-series available for each mooring pair. The moorings across each array are generally well correlated in the along shore direction, with a maximum of 0.86 (zero lag) between SYD100 and SYD140. Upstream of the separation point the correlation between CH070 and CH100 is 0.83, (-1 day lag, CH100 leads). In the across-shelf direction, correlations are much lower, (CH pair 0.65, SYD pair 0.54).

Platform	CH070	CH100	ORS065	SYD100	SYD140	PH100
CH070		0.83 (-1d)	0.34 (29d)	0.37 (27d)	0.32 (30d)	0.38 (12d)
CH100	0.65 (4d)		0.30 (36d)	0.34 (31d)	0.36 (32d)	0.39 (25d)
ORS065	0.13 (28d)	0.07 (240d)		0.85 (-2d)	0.68 (-3d)	0.78 (-3d)
SYD100	0.10 (58d)	0.10 (-43d)	0.30 (1d)		0.86 (0d)	0.68 (0d)
SYD140	0.08 (23d)	0.02 (-2d)	0.28 (-1d)	0.54 (-2d)		0.50 (2d)
PH100	0.18 (217d)	0.30 (-154d)	0.10 (35d)	0.11 (-106d)	0.07 (-236d)	

TABLE II: Maximum correlations and lags in days of the along (black) and across-shelf (grey) components of the sub-inertial depth-integrated velocities. All correlations are significant at the 95% significant level and are computed using the maximum concomitant time-series available for each mooring pair.

An analysis of the shelf moorings in the IMOS program [15], showed that the shelf moorings are well representative of the inter-annual variability when compared with an eddy resolving circulation model, and go some way towards representing the intraseasonal variability. Along the coast of NSW they found that while alongshore correlations were high, there is a region of lower correlation around $32-33°$S, particularly in the velocity-based correlations.

C. Auto-correlation

The required frequency of data acquisition depends on the local dynamics and the range of processes we expect to resolve. A characteristic time-scale has been estimated for each variable, based on the actual $5\ \mathrm{min}$ measurements. These de-correlation time-scales are determined by computing lagged auto-correlations for each time-series and quantifying the maximum lag for which a threshold of 0.7 is obtained (after [5]). For along-shelf velocities, the characteristic (correlation) time-scales increase with the distance from the coast and are higher upstream than downstream of the EAC separation point (as influenced by the EAC). The maximum ($45\ \mathrm{h}$) is found mid-depth at CH100, while the minimum ($6\ \mathrm{h}$) at ORS065 and PH100. This means that a $5\ \mathrm{min}$ sampling frequency is not necessarily required to monitor the large scale along-shelf current. However, across-shelf components at all depths and locations show characteristic time-scales of $30\ \mathrm{min}$ to $4\ \mathrm{h}$, highlighting the need for high-frequency measurements.

The temperature records reveal decorrelation timescales ranging $3-20$ days, with high values (long timescales) at the sensors highest in the water column potentially due to the low-frequency surface flux variability or EAC advection and encroachment onshore. Still, even if this implies that around 50% of the temperature variability is resolved with hourly measurements, we have to keep in mind that higher-frequency processes like internal waves do require high frequency observations.

D. Vertical Correlation

Cross correlations between time series of temperatures at each depth have been estimated. Figure 3 shows the mean resulting correlations as a function of the distance between the temperature sensors, for the 2 moorings located upstream of the separation point. CH070 is midshelf, where as CH100 is near the shelf break and tends to be representative of the EAC proper as it encroaches upon the continental shelf. The 95% confidence limits are not visually distinct from the correlation curves as there are abundant degrees of freedom ($5\ \mathrm{min}$ sampling interval over a 4 year period).

There is both seasonal and interannual variability in the vertical correlation Figure 3. In addition, individual seasons and years are discernible for vertical distances less than $10\ \mathrm{m}$. There is an increasing variability in correlation with increasing separation, e.g $0.7-0.9$ at $10\ \mathrm{m}$, and $0.2-0.85$ at $20-30\ \mathrm{m}$. This can be attributed to seasonal variation as can be seen from the vertical separation between curves of same color (same year) but different symbol (different season). Additionally, a significant anti-correlation can be seen in both platforms for separation distances of greater than $40\ \mathrm{m}$, which increases with increasing separation. This is most evident in the Austral Autumn (MAM) of years 2010 and 2012. This suggests that temperature variation for layers that are separated by distances of more than $40\ \mathrm{m}$ or more vary out of phase (opposite sign). This feature shows the coexistence of a heating source in the upper layer and a cooling in the lower layer, perhaps indicative of EAC encroachment, and associated current driven upwelling [4], [5].

Temperature de-correlates with depth on average faster inshore than offshore, closer to the EAC core (compare the slope of the average (dashed) coherence linesin Figure 3). This is in agreement with vertical mixing being more effective nearer the EAC core. Moorings downstream of the separation point show similar tendencies.

E. Data Quality

Data quality assurance and data quality control are integral components of a sustained observing system. The main goal of a sustained observing system is to produce data streams that are consistently of quality such that they can be readily compared interchangeably with other data streams, collected on different platforms and with different sensors. Unfortunately the effort required to achieve this goal was initially underestimated and hence under budgeted. While describing Quality Assurance (QA) and Quality Control (QC) procedures is not the goal of this paper, suffice it to say that rigourous QA and QC procedures needed to be developed and standardised across the observing system. Data needs to undergo multiple

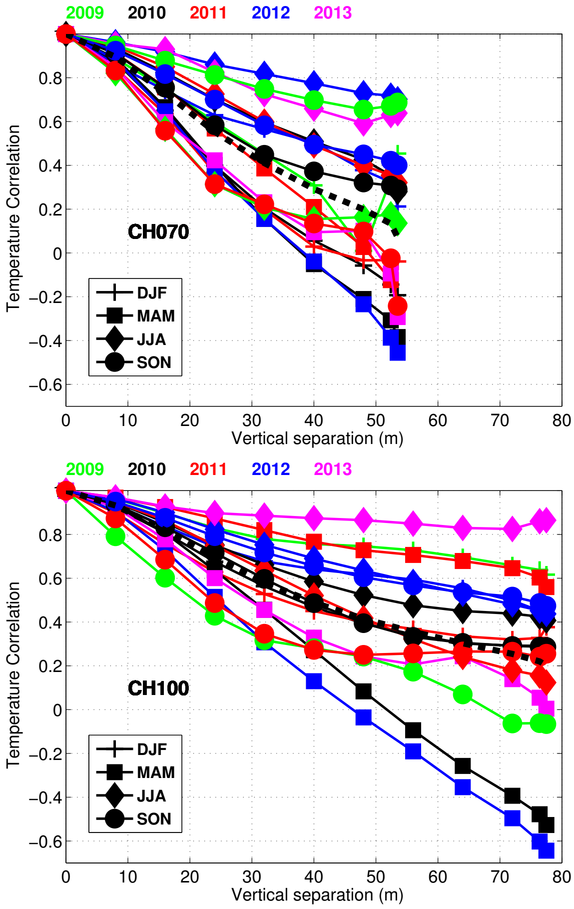

Fig. 3: Temporal average of the vertical correlations between temperature records for CH070 and CH100. Different colors correspond to different years (2009 to 2012), and different symbols show the average over 3 months during different seasons. The dashed line indicates the overall correlation as function of vertical separation.

levels of QC including manual expert QC. Each of these data streams must be archived and versioned. Even six years after the first NSW-IMOS moorings were deployed small data quality issues are still being identified. We suggest that it is only with rigorous uptake and use of the data streams for scientific purposes that these issues will be identified and resolved.

F. Data uptake

Measuring the impact of an observing system through data uptake is a noble task, but not without challenges. The IMOS program is funded as an infrastructure program (number of assets deployed) however longevity of the program will be assessed through the quality and utility of the data streams that are provided. While data users are required to register their consent to the data use policy, which includes acknowledgement of the program and the funding agencies, no tracking devices are deployed. Hence it is difficult to measure the data uptake. That said, a number of high quality publications making use of NSW-IMOS data are starting to appear in top rate journals. These include but ar not limited to studies investigating the design of the array, [1], [16], multi-platform investigations into EAC eddies [7], [17], wind forcing [18], current and wind driven upwelling dynamics [5].

IV. Discussion and Recommendations

A. Consolidating the array in the face of short term budget cuts

Using the metrics defined above to assess the array we can now make an informed decision regarding consolidation of the array in the face of short term budget cuts. Scientific data uptake suggests that the CH pair (upstream of the EAC separation point) in addition to the SYD line (downstream of the EAC separation point), are the most useful lines for capturing the main shelf dynamics of the EAC. This is due to a combination of them being shore normal arrays, with the longest time series, and with the best quality data. Length of the timeseries and the sensor record suggests that the Narooma pair might be the first to go (being the shortest record). However, length and quality of the timeseries does not take into account scientific interest, and there are a number of strong scientific reasons for maintaining this array should more funding become available.

Vertical correlations show that we cannot decrease the vertical sampling density, and that 8 m observations should be retained. Further, the autocorrelation shows that the temporal sampling is also important in capturing the cross-shelf and internal dynamics. Spatial correlations across the shelf show that the PH100 record is well correlated with the ORS065 (0.78) and SYD100 (0.68) moorings, and as it stands alone (not in an array) it could also potentially be sacrificed, although our analysis does not measure the benefit of the mooring to the long term hydrographic sampling at this location. Finally, the SYD100 mooring, is potentially redundant, as it is highly correlated with the ORS065 and SYD140 in both alongshore, (0.85, 0.86) and (less so) the across-shore (0.3, 0.54) directions.

B. Funding Time frames

One of the challenges of IMOS is that there is a mismatch between the funding timescale and the observational timescale. We are attempting to build a multi-decadal observing system but are faced with multiple short-term political funding timescales. This can create an unfortunate situation where we face successive significant budget cuts and followed by subsequent funding injections and thus improvement of the array in the next funding cycle. It is extremely challenging to retain data continuity under such circumstances. To address this mis-match in funding timeframes the National IMOS office has coordinated the writing of an IMOS decadal plan and they are working hard at the Federal level to secure long term funding to secure the future of the program.

C. Recommendations for improvements to the array

1) Moving Existing Moorings: Through an initial assessment of the data we are able to make some recommendations for moving the locations of a number of moorings. As the offshore moorings at CH and SYD are well correlated with the inshore/midshelf moorings, moving the outer mooring further offshore is desirable - however there are limitations in the distance from the coast safely achievable in a day trip, as well as the flotation needed as the current gets stronger.In the case of SYD100, it appears that the mooring was placed in a topographic anomaly (ie the flow is steered by local bathymetry), hence less representative of the general shelf flow [5]. Now is potentially an opportunity to move this mooring inshore slightly.

2) Adding New Moorings/Sensors: There remains still a fundamental mismatch between biology and physics. Our shallowest mooring is in 65 m, where as the majority of benthic ecology interest is in less than 30 m of water adjacent to the coast. State government interest is within 3 nautical miles of the coast. Adding an inshore mooring to both the Narooma (BMP) and Coffs Harbour (CH) lines would be of great benefit to both these communities.

An additional mooring pair at $32 - 33°$ S in the Stockton Bight green zone [13], [15] has always been part of the design when more funding becomes available. This is still required with CTD, and FLNTU as well as velocity. It has been suggested that an improvement to the array could be the inclusion of surface salinity at the inshore mooring locations to asses the impact of coastal runoff.

Finally, striving towards real time data acquisition and delivery is a way to ensure that data uptake within the local community improves. In the context of sustained observing systems, there is also the idea that doing less, but doing it better is preferable. None the less, the sooner these changes are made the better, such that the long term time series is not affected.

D. Numerical Modelling

At the time that the observing system was going through the design phase numerical modelling capabilities were fairly limited. Previous studies had focussed on climatological conditions [19], [20], or idealised scenarios to understand the upwelling dynamics of the EAC e.g [20], [21] and the biogeochemical response e.g. [22], [23] and subsequent connectivity [9].

Recent work of [24] has improved upon the early POM studies by using ROMS at $\approx 1 - 3$ km resolution along the length of the EAC. Such new work is starting to shed light on the role of EAC eddies both meso scale and submesocale eddies, which are only now starting to be observed (through high resolution HF radar and moored observations) - the dynamics of which are still poorly understood. Future goals include data assimilation modelling to assess the design of the observation system and its ability to capture and better predict the key dynamics along the coast. Unfortunately the Australian National IMOS program does not include funding for numerical modelling work to integrate the observations, so these funds must be sought elsewhere, generally through competitive grant funding.

Acknowledgments

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